# Rotor Ice Testing of a Centrifugally Powered Pneumatic Deicing System for Helicopter Rotor Blades

#### FINAL REPORT NASA AWARD NUMBER: NNX13AB78A

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A novel pneumatic approach to protect helicopter rotor blades from ice accretion is presented in this paper. The system relies on centrifugally generated pressures to deform a 0.508 mm (0.02 in.) thick titanium leading edge cap. The leading edge cap is protected by a 10 µm (390 microinch) thick Ti-Al-N erosion resistant coating, Beneath the titanium leading edge, six (6) pneumatic diaphragms were installed. The diaphragms are normally deflated under vacuum against the surface of the blade, and are inflated when ice accretion thickness reaches a critical value. The deformation of the leading edge introduces transverse shear stresses at the interface of the ice layer that exceed the ice adhesion strength of the material (868 KPa, 126 psi), promoting instantaneous ice debonding. The applied input pressures to the system (+/- 25.5 KPa, 3.7 psi) were representative of the pressures generated centrifugally by a medium helicopter size rotor system. With these pressures, the maximum deformation of the leading edge was quantified to be 5 mm (0.2 in). The aerodynamic performance degradation effects related to the leading edge deformation were quantified during low speed (1 M Re) wind tunnel testing. Results were compared to the aerodynamic performance degradation due to ice accretion. It was measured that the penalties related to the deployment of the pneumatic diaphragms was 35% lower than the aerodynamic drag penalty due to ice accretion. The lower aerodynamic penalty of deploying the proposed deicing concept with respect to that of ice accretion case indicates that the system would not introduce any aerodynamic penalty while removing accreted ice. The system was tested under representative rotor icing conditions and at centrifugal loads that ranged from 110g to 514g. The deicing successfully promoted instantaneous shedding of ice layers ranging from 1.5 to 5 mm (0.06 in. to 0.1 in.) in thickness for varying icing conditions within FAR Part 25/29 Appendix C Icing Envelope.

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## I. Introduction

When rotorcraft enter an icing environment, super-cooled water droplets impinge on the leading edge of the rotor blades [1]. The water droplets freeze on impact with the rotor. Rotor ice accretion degrades the vehicle performance and handling qualities [2]. The noise and vibration levels of the vehicle are adversely affected. Helicopter icing is prevalent over fixed-wing given the typical mission of the vehicle: urgent transportation or search and rescue at low altitude, high humidity environments. Electrothermal deicing is the only system certified by the Federal Aviation Administration and used by DoD to protect helicopter rotor blades. Electrothermal deicing is used to melt the ice interface between accreted ice and the leading edge erosion protection cap of the rotor. Extensive ice testing of the S-92 conducted by Flemming et al. [3-5], has demonstrated the reliability of thermal deicing systems for larger vehicles. For these types of vehicles (>10,000 lb empty weight), ice accretion is not a major concern due to the availability of sufficient electrical power and payload to implement robust electro-thermal ice protection systems. Such a system requires large amounts of energy (up to 3.9 W/cm<sup>2</sup> or 25 W/in<sup>2</sup>) and contributes to an undesired increase in the overall weight of the system and cost of the blade. The high power consumption of this system limits the time that it can be active and the surface area that can be protected. Those areas not protected during deicing continue to accumulate ice until the heating mats under that specific leading edge region are turned on. During some occasions, melted ice might flow to the aft portion of the blade (where there are no heating mats) to refreeze. Since the electro-thermal deicing system melts the ice interface, ice shedding occurs under centrifugal loading. Released ice patches that could reach up to 7.6 mm in thickness [1], are a ballistic concern for some vehicles since control of the ice release azimuthal position has not been implemented to date using electrothermal deicing. The system relies on the thermal conductivity of isotropic materials to protect the leading edge of the blade from erosion. For this reason, electro-thermal deicing is not suitable for new polymer based leading edge protection coatings that have lower thermal conductivity. A major disadvantage of electro-thermal deicing is that the electrical power required substantially exceeds the normal helicopter electrical system capacity, requiring a secondary electrical system with redundant, dual alternator features [1]. The weight related to the required electrical power can be as large as 112 Kg (245 lbs) on a 4,300 Kg (9,500 lbs) gross weight helicopter [1].

A non-thermal, low-power deicing system, would allow for the implementation of ice protection systems to smaller vehicles. The low-power consumption would eliminate the need for high power slip ring requirements. The non-thermal quality of the deicing system would also allow its application to blades protected with novel erosion resistant coatings that might have low thermal conductivity. Efforts to come up with a non-thermal, low-power mechanical deicing system are on-going. The technologies being investigated include ultrasonic deicing [6, 7], blade resonance [8, 9, 10], electro-impulsive deicing and the use of eddy currents [11]. Mentioned technologies have their own drawbacks related to rotor blade implementation complexity, robustness, reliability and weight.

Pneumatic deicing systems have been successfully used in fixed-wing applications for decades and it was implemented to helicopter rotor blades back in the 80's [12]. Though the pneumatic boots were successful at removing accreted ice, complicated pneumatic slip-ring needed to transfer the air pressures from the fixed frame to the rotor blades, coupled with erosion of the pneumatic boots did not warrant a continuation on the technology development. To address the drawback related to prior tested pneumatic deicing configurations, it is proposed to use centrifugal pressure inherent to the rotor blade to actuate a pneumatic deicing system. Centrifugal pumping would eliminate the need of pneumatic slip rings. The proposed pneumatic actuation on rotor blades relies on pressure differentials created by the acceleration of air inside the blades as they rotate. A schematic of the created pressure differential between two volumes placed along the span of a blade is depicted in Figure 1. The capability of a rotor blade to generate 7.2 psi pressure differential was experimentally validated on a full scale rotor blade system. This technology is patented by Invercon LLC (*Pneumatic Actuator System for a Rotating Blade*, EFS ID: 9369871, Application Number:

13020333). The theoretical pressures created inside a rotor blade instrumented with two pressure lines can be derived from the hydrostatic equation of the fluid:

$$\frac{dp}{dr} = \rho(r)r\Omega^2 \tag{1}$$

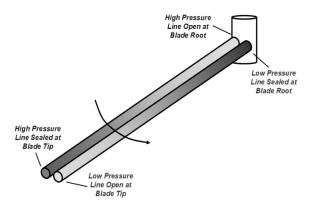


Figure 1. Schematic of low and high pressure lines under rotation. Pressure differential between the lines to be used for pneumatic deicing deployment

Issues related to pneumatic deicing boot erosion are proposed to be solved by using titanium nitrade based erosion resistant coatings applied over 0.508 mm thick (0.02 in.) titanium substrates. This coating has demonstrated excellent erosion resistance compared to metals [13, 14].

#### II. Objectives

The goal of this research effort was to design, fabricate and test an innovative centrifugally powered pneumatic deicing system. The following objectives were identified: 1) to design and fabricate a pneumatic deicing prototype for wind tunnel aerodynamic testing; 2) design and fabricate a pneumatic deicing prototype to be tested under representative rotor icing conditions and centrifugal loads; 3) conduct experimental testing of a centrifugally powered pneumatic deicing system for helicopter rotor blades; 3) to confirm the pneumatic deicing system effectiveness under representative icing conditions and centrifugal loads; 4) to confirm low-power consumption, erosion resistance, and quantify aerodynamic performance penalties; 5) to confirm that ice debonding azimuthal rotor position can be controlled to avoid ice ballistic concerns upon shedding.

## III. Prototype Design

The conceptual integration of the pneumatic deicing prototype is shown in Figure 2. The design considered allowed for local deformation of a 0.508 mm (0.02 in) thick titanium grade 2 leading edge cap. For the proof-of-concept testing conducted during this research, readily available polyolefin tubing was used to fabricate the pneumatic diaphragms.

The configuration attempts to reduce the blade modifications needed to integrate the system. Ideally, the system should replace currently used metallic erosion resistant leading edge caps. For this reason, the thickness of the proposed system is similar to rotor blade erosion caps: the overall thickness of the pneumatic diaphragms, titanium leading edge substrate, and erosion coating (Ti-Al-N, 10 µm thick) was

targeted to be 1.27 mm (0.05 in.). This thickness is representative of that of existent rotor blade metallic leading edge caps. As the pneumatic diaphragms expand under the leading edge cap, localized ice interface transverse shear stresses, responsible for ice delamination, are introduced. The Ti leading edge cap was designed as a single smooth piece to limit aerodynamic performance penalties related to leading edge shape changes upon system inflation.

## IV. Aerodynamic Testing

Prior to rotor ice testing, aerodynamic testing of the proposed prototype was conducted. A photograph of the NACA 0012 (40.64 cm chord) installed in the wind tunnel with the pneumatic deicing treatment is shown in Figure 3. In this same figure, side views of the un-deployed and deployed system are shown. The maximum deflection of the aft location of the leading edge cap was measured to be 5 mm with respect to the airfoil surface. This measurement was taken when all the diaphragms were inflated. It must also be noticed that the leading edge spacing available for the installation of the system was oversized to 5 mm to facilitate its installation. The pneumatic deicing prototype only needed 1.27 mm (0.05 in.) gap to be mounted flush with the leading edge shape of the airfoil.

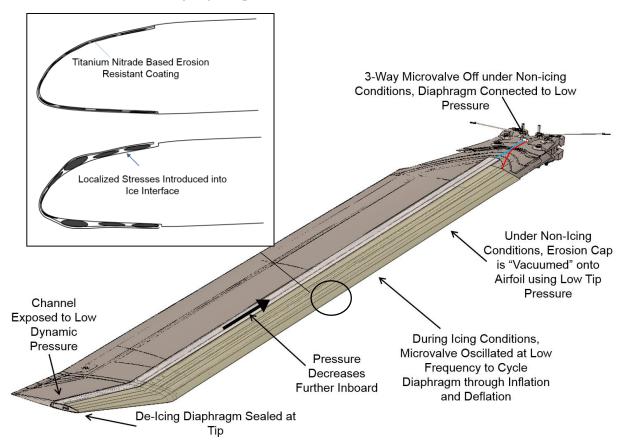


Figure 2. Schematic pneumatic deicing integration to a representative helicopter blade

The model shown in Figure 3 was tested in a 60.9 cm x 91.4 cm (24 in. x 36 in.) subsonic wind tunnel (turbulence 0.2%). Wind tunnel measurements were conducted at 1M Re (36 m/sec flow velocity). Lift and drag measurements were done using a load cell which had a resolution of 0.69 N (1/64 lbs.). The measured lift and drag coefficients for the un-deployed (airfoil shape) and deployed system is shown in Figure 4. The

experimental results are compared to predictions for a NACA 0012. The discrepancies between the predicted lift and drag coefficients and those measured for the un-deployed configuration are attributed to the prototypical nature of the leading edge. The body of the airfoil was machined out of solid aluminum using a 3-axis CNC and it matches the shape of a NACA 0012 airfoil, but the leading edge cap (bonded to the diaphragms) was bent to shape with a press that deformed a plate into a female mold. The fabrication procedure for the leading edge did not provide an exact NACA 0012 shape, as it is apparent on the disparities between lift and drag coefficient predictions and measurements for the un-deployed configuration. Despite the shortcomings related to the leading edge fabrication, the changes between the un-deployed configuration and the deployment of the pneumatic deicing system were quantified. The drag of the deployed configuration increases by 4.5 times the drag of the un-deployed configuration at an angle of attack of 10 degrees.

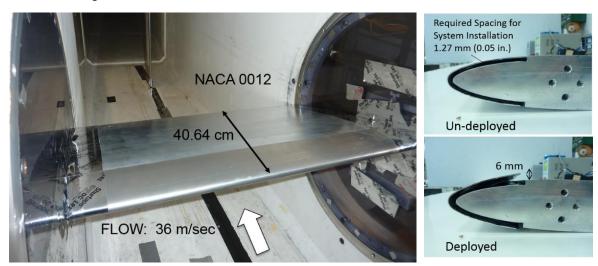


Figure 3. Photograph of wind tunnel model with pneumatic deicing prototype and side view of undeployed and deployed system

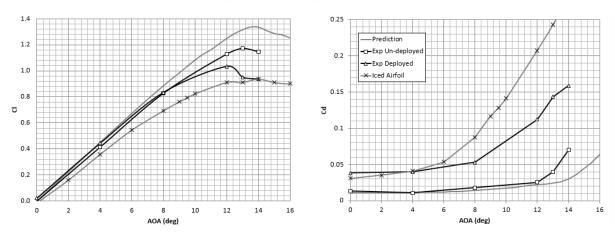


Figure 4. Predicted and measured lift and drag coefficients for a NACA 23012 with pneumatic deicing treatment. The iced airfoil values were obtained from Ref. 15

In Figure 4, the measured drag for an ice shape reported in Reference 15 is also shown. The drag increase due to the pneumatic deicing deployment is less than the drag introduced by the accretion of ice, which is 6.8 times larger than the drag of the un-deployed configuration (also at 10 degrees angle of attack). Similar trends are observed on the lift penalties. The aerodynamic penalty related to the deployment of the

pneumatic deicing system is inferior to that introduced by ice accretion by a factor of 2.3. This indicates that deploying the pneumatic deicing system will not negatively influence the blade aerodynamic performance if ice has already accreted to the blade.

During wind tunnel testing, all the diaphragms between the airfoil and the leading edge protection cap were inflated simultaneously with an input pressure of +/- 25.8 KPa, or 3.75 psi. The inflation of all the diaphragms corresponds to the maximum leading edge shape variation possible when actuating the pneumatic deicing technology.

# V. Ice Adhesion Strength Testing of Proposed Coating

Nitride-based coating materials were selected as erosion resistant coating due to their high hardness, good corrosion and oxidation resistance. These materials can be deposited with relative ease as both monolithic and multilayer coatings using reactive cathodic arc evaporation and/or sputtering with coating thicknesses greater than 10 microns. Nitride-based coatings with moderately high hardness and a fine grain structure exhibited nearly an order of magnitude less erosion than titanium. Two nitride configurations were investigated looking into ice adhesion strength: titanium nitride and titanium aluminum nitride. The adhesion strength was measured as the ratio of the loads needed to centrifugally remove accreted ice over the area of removed ice. An instrumented rotor system measured ice shedding (Figure 5).

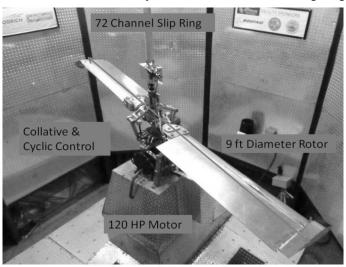


Figure 5. AERTS photograph with ice adhesion strength rotor system.

The blades used for these experiments were specially designed for determining ice adhesion strength during prior research efforts. The tips of the blades house a beam that bends under centrifugal loading. A full Wheatstone Bridge senses the bending strain and filters out axial loads and temperature changes. As the test coupon, attached to the tip of the beam accretes ice, the centrifugal force on the beam increases due to the additional ice load, and the beam bends in the span wise direction. The strain gauges measure the additional deflection of the beam given the ice accretion. A photograph of the rotor tip beams and the assembled system is shown in Figure 6.

As the beam bends outward along the span direction, the voltage read across the strain gauges decreases. When the ice has accreted a large enough mass such that the centrifugal load surpasses the ice adhesion strength of the test material, the ice de-bonds and sheds off. The event is captured by a sharp increase in voltage from the strain gauges as the beam retracts. An example of the beam relaxation upon ice shedding is shown in Figure 7.

The sensors are calibrated during each test by knowing the tip mass  $(M_{tip})$ , the blade length (R), the voltage read by the strain gauges at zero RPM  $(V_0)$ , and the voltage read by the gauges at the desired operational RPM  $(V_{RPM})$ . The ice load is extrapolated using the voltages read by the strain gauges at a shedding event. The calibration and ice load calculation is depicted by Figure 8 and summarized by Equation 1. Once the ice sheds, the ice shed-area is determined from measuring the area by using graph paper, as depicted in Figure 9. The ice adhesion strength is determined as the ratio of the ice load prior to shedding over the shed area (Equation 2).

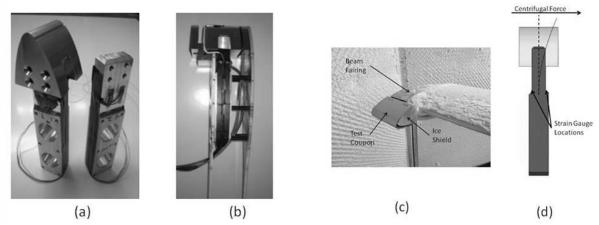


Figure 6: (a) Adhesion beam with exposed strain gauges, (b) Adhesion beam tip assembly, (c) Adhesion beam with blade assembly, (d) Adhesion beam with exaggerated bending center line

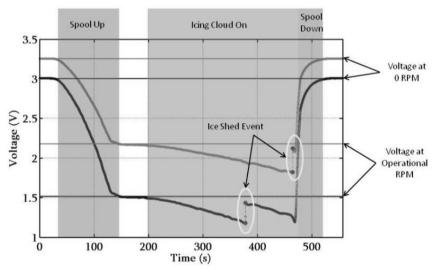


Figure 7: Example of voltages read from strain gauges during test

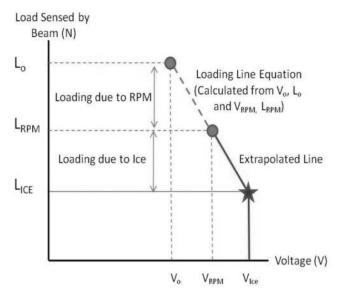


Figure 8: Ice Load Calibration

Calibration Slope = 
$$\frac{M_{tip}R\left(RPM*\frac{\pi}{30}\right)^2}{V_{RPM}-V_0}$$
 Equation 1

$$Adhesion Strength = \frac{(V_{shed} - V_{final}) * Slope}{area}$$
Equation 2

The novelty of this ice adhesion strength measurement procedure is the hands-off approach. There is no operator interaction with accreted ice that could introduce outside influence into the ice adhesion strength results. Some ice shedding techniques accrete the ice in an icing wind tunnel, and then the accreted ice is transported to an ice removal rig. During the transportation of the accreted ice, potential mechanical and thermal stresses could be introduced, polluting the ice adhesion strength results, and explaining the large spread in ice adhesion data to date. In addition, a mechanical force ice removing system might introduce unwanted moments on the accreted ice for different ice shapes, providing fictitiously low results. Further details of ice shedding measurement procedures can be found in Ref. 15.

Results indicate that TiN has lower ice adhesion strength than TiAlN for an equal temperature and surface roughness (Figure 10). For this reason, TiN is selected to coat the pneumatic de-icing system for erosion protection. The ice adhesion strength of the nitrade base materials was compared to that of stainless steel, inconel 625, and titanium grade 2.

Since the samples have slight variations in surface roughness with respect to the desired roughness values, the materials were compared by eliminating the effect of temperature from the data and plotted in terms of an adjusted adhesion strength (AAS) values as a function of surface roughness. To develop the adjusted adhesion strength, each adhesion strength value in the test matrix is divided by the ambient temperature for that test (see Equation 3). The three adjusted values for each surface are averaged to calculate one adjusted adhesion strength value for each surface roughness value (see Equation 4). The effect of temperature was eliminated due to the fact that ice adhesion strength varies linearly with temperature [15] for the range tested. The data was reduced by dividing adhesion strength by the ambient temperature and averaged to produce one temperature-adjusted adhesion strength value for each surface roughness.

$$x_i = \frac{Adhesion\,Stength}{Temperature}$$

$$AAS = \frac{\sum_{i}^{3} x}{3}$$
 Equation 4

The temperature-adjusted adhesion strength for all of the materials is shown in Figure 10. The arrow signifies the estimated lower limit of adhesion strength for the TiAlN sample. TiAlN had the strongest dependence on surface roughness followed by TiN and stainless steel 430, then Inconel 625 and titanium grade 2. Stainless steel 430 had an average temperature-adjusted adhesion strength of 4.2 psi/°C, Inconel 625 had an average of 3.7 psi/°C, Titanium had an average of 3.1 psi/°C, TiN had an average of 4.7 psi/°C, and TiAlN had the highest average with 6.3 psi/°C without being able to properly test the high surface roughness range. The manufacturing technique for the coatings has not been optimized the *PV* roughness while maintaining *Ra*. Until the *PV* values of the coatings are brought down to similar values as the substrate, it is an unfair comparison. A summary of temperature adjusted adhesion strength values can be found in Table 1Error! Reference source not found.

Table 1: Summary of average temperature adjusted adhesion strength values

	psi/°C		
Stainless Steel 430	4.2		
Inconel 625	3.7		
Titanium Grade 2	3.1		
TiN	4.7		
TiAlN	6.3		

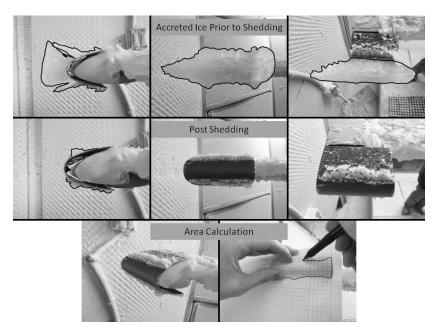


Figure 9. Pre and post ice shed photos and area measuring technique.

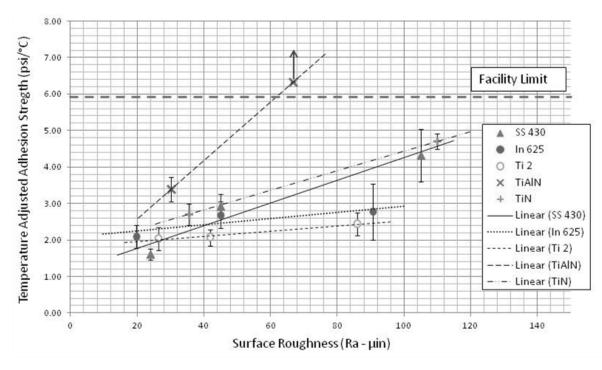


Figure 10. Comparison of temperature adjusted ice adhesion strength.

# VI. Erosion Resistance

The erosion resistance capabilities of the Ti-AL-N coating were evaluated and compared to titanium grade 5. A summary of the results is shown on Figure 11. The erosion rate of the surface treated with Ti-Al-N is orders of magnitude lower than that of Ti grade 5, demonstrating the excellent capability of the selected coating to protect against sand erosion. The surface of the titanium baseline and two coating thickness (10 and 20  $\mu$ m) was imaged before and after erosion with a Scanning Electron Microscope (SEM). The comparison of the surface images is shown in Figure 12, demonstrating the coating capability to protect against sand erosion. The use of erosion resistance coatings with the proposed system is an option to increase the life of the system, but not a requirement for the implementation of the technology. Titanium leading edge caps without coating protection would also provide ice protection to the blade while maintaining current erosion resistance capabilities.

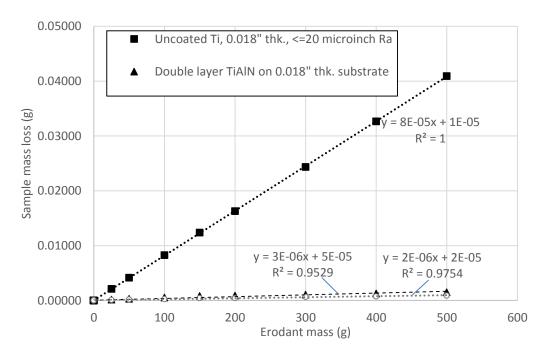


Figure 11. Erosion testing results for Ti and Ti-AL-N

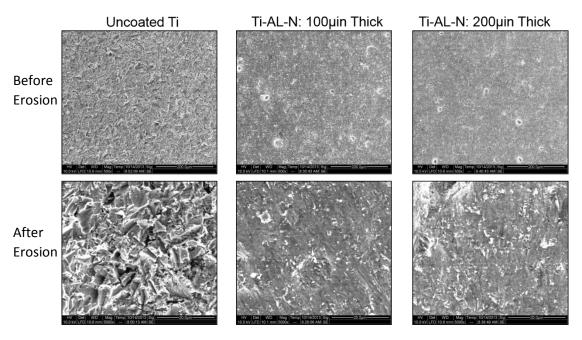


Figure 12. SEM Surface Morphology 500 g. exposure, 30 degrees, 156m/s, 50 μm alumina, 0.5 wear diameter, 22 cm. stand-off distance, 100g/min

# VII. Pneumatic Deicing Modeling

The pneumatic deicing concept introduces ice interface delamination stresses responsible for ice debonding. Knowing the ice adhesion strength of the erosion resistant coating is critical to predict the required interface transverse shear stresses needed to promote ice delamination. The ice adhesion strength of impact icing to Ti-Al-N was quantified by Soltis et al. [17]. The ice adhesion strength of Ti-Al-N with a surface roughness

of approximately 0.76 µm (30 microinches) was quantified to be as high as 6.3 psi/ $^{0}$ C. As per the FAR Part 25/29 Appendix C Icing Envelope, the coldest temperature at which in-flight icing conditions are encountered is -20 $^{0}$ C [18]. At this temperature, the shear ice adhesion strength of Ti-AL-N is estimated to be 868 KPa (126 psi). This ice adhesion strength is the maximum critical ice interface transverse shear stresses that the pneumatic deicing configuration must overcome to promote ice delamination. Based on this ice adhesion strength value, the deformation of the leading edge needed to promote ice delamination was calculated.

The ice adhesion cohecsive failure is modeled following similar principles used in the modeling of composite delamination. Composite delamination has been successfully modeled and predicted using cohesive damage models and fracture mechanics in the past. Experimentally determined values of interfacial bond stiffness, strength, and fracture energy in pure mode I, II, and III are used to define cohesive elements along the bond line. The bond strength of ice has been successfully determined at a given temperature, surface roughness, and type of ice. Under the assumption that metallic-ice interfaces fail under a known stress state, the same methods used to predict composite delamination can be applied to ice interfaces.

The goal of our FEM modeling is to develop a tool which can accurately predict delamination of an ice-metallic interface due to surface deformation. Once this behavior has been verified, the same techniques can be expanded to rapidly determine the effectiveness of different pneumatic de-icing system designs as well as the optimal method of deployment. The cohesive material properties which define the ice adhesion strength have been adopted from a paper by Riahi et al [19]. Riahi performed the tests required to quanitfy the necessary FEM calibration coefficients. From this investigation Riahi concluded that their approach can be used in failure prediction of ice/substrate structures. Table 2 depicts the necessary cohesive zone properties of an ice/aluminum interface.

Table 2: Cohesive material properties used in the FE model for Ice/Al interfaces (-10° C)

Abaqus Option	Interface Properties	Values	
Elastic	Cohesive layer modulus (penalty stiffness)	1.0 x 10 <sup>6</sup> N/mm <sup>3</sup>	
(type = traction)	in all 3 directions, K <sub>nn</sub> , K <sub>ss</sub> ,K <sub>tt</sub>		
Damage initiation	Ultimate strength in tensile, T	$0.8 \times 10^6 \text{ N/mm}^2$	
(criterion = quads)	Ultimate strength in mode II, S	$0.8 \times 10^6 \text{ N/mm}^2$	
	Ultimate strength in mode III, N	$0.8 \times 10^6 \text{ N/mm}^2$	
Damage Evolution	Normal mode fracture, G <sub>IC</sub>	1.0 x 10 <sup>-3</sup> N/mm	
(type = energy)	Shear mode fracture, G <sub>IIC</sub>	2.0 x 10 <sup>-3</sup> N/mm	
	Shear mode fracture, G <sub>IIIC</sub>	2.0 x 10 <sup>-3</sup> N/mm	

A 2-D model was created which matched the leading edge geometry of an NACA-0012 airfoil used during wind tunnel testing, Figure 13. The model includes accurate geometries of the leading edge, aluminum substrate, pneumatic bags, and rubber stoppers. Applying identical pressure and vaccum to the pneumatic bags in the FEM model provided accuarte displacements as compared to experimental testing (discrepancies in displacement of less than 5%).

Representative ice shapes were tied to the surface of the leading edge in the FEM using the cohesive surfaces defined by the cohesive zone properties found in Table 3. Ice shedding was predicted for the conditions tested in this report using the proposed tool (Figure 14).

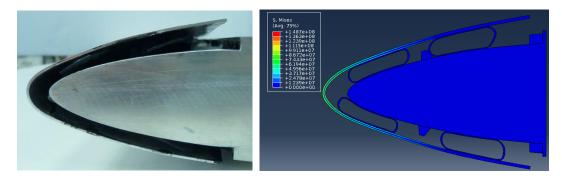


Figure 13. Photograph and FEM model predicting deformation and stresses due to system inflation

Table 3: Material properties used in FEM

Material	Young's Modulus (Gpa)	Poisson's ratio	
Aluminum	69	0.20	
Ice	9	0.27	
Elastomeric Bag	0.075	0.50	

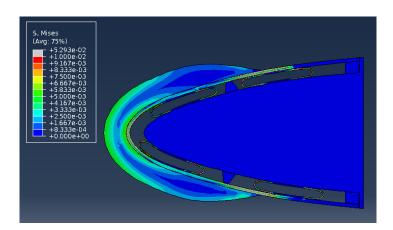


Figure 14. FEM snapshot in time during the deployment of the pneumatic de-icing system. Stresses developed in the ice are recorded.

The pneumatic de-icing system was modeled as "one" part due to the complex geometries and small tolerances in this particular structure. This part includes the base, bags, stoppers, and leading edge cap. Geometric partitions are used to specify individual materials within the part. The 0.25 inch thick ice shape was designed separately to match the leading edge shape and to be representative of rime ice conditions.

When calibrating the model and searching for model convergence the ice is not included in the model. Later the ice is simple added to the assembly along the leading edge. The simplicity of the assembly module is traded for complexity of the interaction module. The bags must all be tied to both the surface of the base and the backside of the leading edge cap. Tie constraints are then applied over the length of each bond, approximately 0.4 inches. The cohesive properties which define the ice/aluminum interface, are also defined in this module when the ice is included. The pneumatic de-icing system is actuated through pressurization of the pneumatic tubes, derived from centrifugal pumping. The pressure/vacuum of +/-4 PSI is applied to the inside surface of each of the bags to simulate this actuation. Just as the pneumatic de-icer

can operate each of these bags individually, so can the model. The entire base is clamped, effectively making it a "rigid" part. While it does not need to be modeled, this section does not add significant computational time, and greatly adds intuitive understanding of the overall system. The converged mesh consists of only 2-D 8-noded biquadratic elements employing reduced integration, CPS8R elements.

In future work, optimization of the pneunmatic de-icing configuration is proposed. The optimization process should include investigation into the minimum displacement required for ice removal, which will decrease any undesired aerodynamic penalites during deployment. Other variables which may be investigated include: number of bags, placement of bags, modified substrate design beneath the leading edge.

## VIII. Rotor Ice Testing

To evaluate the ice protection capability of pneumatic deicing, rotor ice testing was conducted at the Adverse Environment Rotor Test Stand Facility (AERTS) at Penn State [17]. A QH-50 fiber glass blade was truncated to a radius of 1.57 m (62 in). A pneumatic deicing prototype was installed on the outer surface of the blade. The prototype covered a span of 30.18 cm (12 in.) from the rotor tip. The pneumatic deicing system had six (6) independently controlled diaphragms between the QH-50 surface and the 0.5 mm (0.02 in.) thick titanium grade 2 leading edge protection cap. The protection cap was coated with a 10  $\mu$ m (390 microinch) thick Ti-Al-N erosion resistant coating. The chord-wise protection extended 7.62 cm (3 in.) from the leading edge on both the top and bottom surfaces of the airfoil. A photograph of the pneumatic deicing prototype installed on the blade is shown in Figure 15. The ice protective configuration was placed at the tip of a 152 cm radius blade.

The icing conditions tested are summarized in Figure 16. The icing cases evaluated are superimposed on the continuous and intermittent icing envelopes described in the FAR Appendix C. All the icing conditions were tested at 540 RPM (90% span centrifugal load of a 30 ft. long blade at 255 RPM) and 250 RPM (20% centrifugal load of a 30 ft. long blade at 255 RPM). The pressure needed to inflate and deflate the diaphragms was provided by a pneumatic slip ring, since the truncated rotor does not have sufficient radius to generate the required pressures. +/- 25.5 KPa (3.7 psi) were applied to the pneumatic deicing system. Two pressure transducers located at the root of the blade quantified the pressured sent to the deicing system. The selected pressures are within the pressure generation capability by the rotor blade of a medium size helicopter. Power (0.725 W per valve) to the six pneumatic valves located at the root of the blade were sent via a slip ring.



Figure 15. Detail of leading edge pneumatic ice protection system installed on truncated QH-50 blade and photograph of rotor stand

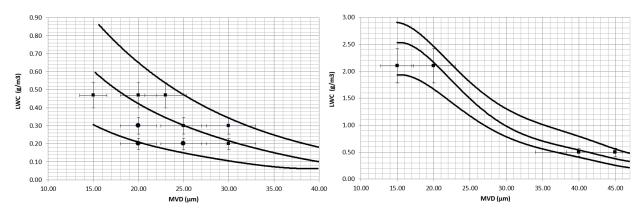


Figure 16. Continuous and intermittent icing envelope from FAR Part 25/29 Appendix C [18] with tested icing conditions

In Figure 16, squares indicate those icing conditions that promoted instantaneous ice delamination of layers of ice with thickness ranging from 0.06 in. to 0.1 in. Those points identified by circles, required higher ice accretion thickness (up to 6 mm) to promote instantaneous ice debonding. Mentioned icing conditions corresponded to cold temperatures in where the ice adhesion strength of the Ti-AL-N coating increases. In addition, it was observed that the polyolefin diaphragms stiffness increased at temperatures below -15°C. The maximum deformation of the leading edge was decreased by almost 40% due to the stiffening of the pneumatic material at cold temperatures. It must be noted, that the diaphragms used were not rated to operate at temperatures below -15°C, and that substitute materials with more adequate temperature ratings would eliminate concerns related to stiffening of the polyolefin material. Also it must be mentioned that 6 mm ice thickness is representative of the minimum thickness required by electrothermal deicing to promote ice shedding. The test matrix completed is summarized in Table 4.

A sample of ice accretion prior inflation of the pneumatic deicing system is shown in Figure 17 a. In Figure 17 b, it can be seeing the protected surface free of ice after actuation of the system under rotation. Ice debonding was promoted during rotation as the leading edge surface deformed, thus introducing ice interface transverse shear stresses that delaminated the ice.

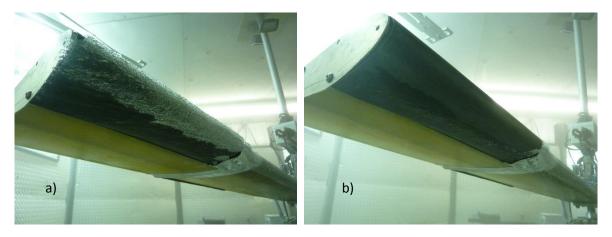


Figure 17. Photograph of ice accretion before and after pneumatic deicing protection (Case 29)

Table 4: Test Matrix Completed. Successful ice shedding obtained for all cases

	MVD	Temp (Deg.		Ice Thickness	LWC	Accretion Time
Test #	(microns)	C)	RPM	(cm)	(g/m3)	(min)
1	20	-18.7	268	0.186	0.2	2
2	20	-17.9	540	0.549	0.2	4.5
3	15	-17.4	268	0.312	2.1	1.5
4	15	-16.7	268	0.270	2.1	0.75
5	15	-16.3	268	0.370	2.1	1
6	15	-15.1	540	0.147	2.1	1
7	20	-14.7	540	0.488	0.3	2
8	40	-14.3	268	0.677	0.5	3
9	40	-14.2	540	0.551	0.5	2
10	30	-12.5	540	0.329	0.2	2
11	23	-11.9	540	0.323	0.47	1.5
12	15	-11.6	268	0.234	2.1	1
13	20	-11.5	540	0.481	2.1	2
14	30	-11.5	268	0.437	0.2	2
15	20	-11.3	268	0.578	2.1	2
16	15	-11	540	0.168	2.1	1
17	25	-9.8	268	0.301	0.3	2
18	25	-9.3	540	0.398	0.3	2
19	20	-8.5	268	0.462	0.47	2.5
20	20	-8.1	540	0.433	0.47	2
21	33	-8	540	0.400	1	2
22	33	-7.9	268	0.536	1	2
23	23	-5.4	268	0.325	0.47	2
24	30	-5.3	268	0.277	0.3	1.5
25	30	-5.3	540	0.190	0.3	1.5
26	30	-5	540	0.315	0.47	2
27	30	-4.9	268	0.187	0.47	2.25
28	23	-4.7	540	0.424	0.47	2
29	45	-4.7	268	0.174	0.47	2
30	45	-4.7	540	0.174	0.47	2

# IX. Conclusions

The design, fabrication and rotor ice testing of a pneumatic deicing prototype for helicopter rotor blades was accomplished. The pneumatic deicing system is conceived to be inflated and deflated at the leading edge of a rotor blade such that ice interface transverse shear stresses promote ice delamination of accreted ice. The pressures needed to actuate the system are envisioned to be obtained from the centrifugal pumping capability of the rotor, eliminating the need for pneumatic slip rings. During the proof-of-concept tests performed during this research, due to the truncation of the rotor system, a pneumatic slip-ring was used to

transfer +/- 25.8 KPa (+/-3.7 psi) to the deicing system. The pressures used are representative of the pressures available on a representative full-scale rotor, and as experimentally measured in a full-scale rotor system during prior research.

From the conducted research, the following conclusions can be made:

- 1) The drag aerodynamic performance degradation of the proposed system due to deployment was quantified to be less than the negative effects of ice accretion by a factor of 2.3 at 10 degrees angle of attack. This trend was observed for other angles of attack.
- 2) The sand erosion resistance of the system was demonstrated. The proposed Ti-AL-N coating used showed to increase the erosion rate resistance capability of the deicing system surface by two orders of magnitude.
- 3) The ice adhesion strength of the proposed erosion resistant material was quantified. This ice adhesion strength value was used during the modeling efforts of the system as the critical shear value that must be created by the configuration to debond accreted ice.
- 4) The proposed pneumatic deicing configuration successfully protected the rotor from dangerous ice accretion under rotor icing conditions at 20% and 90% centrifugal load of a representative vehicle.
- 5) The system was able to instantaneously delaminate ice accretion for points within the Appendix C icing envelope, with Liquid Water Concentrations varying from  $0.2~g/m^3$  to  $2~g/m^3$ , Median Volume Diameter droplets changing from 15 to 45  $\mu$ m, and temperatures varied between -18.7°C to -4.7°C.
- 6) Ice accretion thickness as small as 1.5 mm (0.06 in.) were successfully removed for temperatures above -15°C. The maximum ice thickness needed to promote ice delamination at colder temperatures was quantified to be 6 mm (0.2 in.), which is a comparable thickness to that allowed by state-of-the-art electrothermal deicing. The reason for the increase ice thickness requirements was attributed to stiffening of the pneumatic diaphragms at cold temperatures as well as the increase in ice adhesion strength of the material.

# X. Acknowledgements

This project was funded by NASA Leading Edge Aeronautics Research Grant Number NNX13AB78A. The authors would like to acknowledge our valuable interaction with Richard Eric Kreeger at NASA Glenn Research Center. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Aeronautics and Space Administration. The U.S. Government is authorized to reproduce and distribute reprints for Government purposes notwithstanding any copyright notation thereon.

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